Comment

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A new Progressive Management Pathway for improving seaweed biosecurity

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The rapid expansion and globalization of the seaweed production industry, combined with rising seawater temperatures and coastal eutrophication, has led to an increase in infectious diseases and pest outbreaks. Here, we propose a novel Progressive Management Pathway for improving Seaweed Biosecurity.

The rise of seaweed cultivation

Seaweed cultivation is rapidly expanding globally. The leading region for seaweed production is Asia, although other regions (i.e., South America, Africa and Europe) have increasingly begun to cultivate selected seaweeds in response to rising global demand for a wide range of products dedicated to human consumption, such as food, cosmetics, pharmaceuticals and nutraceuticals. Other uses include agricultural fertilisers, livestock feed, biofuels, biomaterials used, for example in food packaging, and more recently the capture of atmospheric carbon[1].

Currently, seaweed production accounts for ~51% of total global marine and coastal aquaculture production by volume, equating to nearly 35 million tonnes[2]. Exponential growth of the seaweed industry, particularly in the last 50 years, resulted in the sector reaching USD 14.7 billion in 2019[2]. Seaweeds are cultivated in over 54 countries worldwide[2] at various scales, from less than one to many thousands of hectares[3]. The seaweed industry provides jobs to over 6 million farmers, predominantly in coastal communities in low and middle-income countries. These communities mostly sell their seaweed products to foreign, multi-national companies for processing and export[3].

Problems derived from a lack of seaweed biosecurity guidelines

The rapid expansion and globalization of the seaweed industry, in combination with escalating climate change-related events, and a rise in eutrophication of coastal environments, has led to an increased prevalence of infectious disease and pest outbreaks[4]. The Philippines alone, recorded an income loss of USD 32 million between 2011–2012, due to seaweed disease outbreaks, such as Ice-Ice disease (IID) and epiphytic filamentous algae (EFA) (Fig. 1), poor quality cultivars (i.e., infected) and natural disasters[5]. In China, disease losses in *Porphyra* farming alone reached USD 410 million in 2021[4]. Similar economic losses across a broad range of seaweed species have also been seen in the Republic of Korea, Tanzania, and Indonesia[3].

Research to identify seaweed diseases and pests, including viruses, bacteria, protists and eukaryotic endophytic algae, is ongoing[6]. However, we have only seen recent evidence of measures applied for seaweed disease prevention, treatment, and mitigation[5,7]. The control of grazers, epiphytes, and competing invertebrates, coupled with fouling algal outbreaks, which deter seaweed growth, is particularly difficult to manage. This is especially true for seaweeds grown under open sea conditions, as compared with land- or pond-based animal aquaculture production systems, where external conditions and hazards may be easier to mitigate[8,9].

Our recent work has, however, proven the effectiveness of relatively simple biosecurity measures in Malaysia, such as the use of healthy, uninfected propagules, regular simple cleaning of the seaweed thallus and farm ropes to remove biofouling and early identification of infected stock. These measures significantly reduce the incidence of disease and epi-endophytes in red algal carrageenophytes *Kappaphycus* spp. throughout the entire cultivation period, improving both seaweed quality and market value[8]. In China, the use of bleaching powder or potassium permanganate is now routinely applied to the water supplies in seedling nurseries to prevent the growth of the main pathogenic microorganisms that are known to cause disease in the seedlings of the kelp *Saccharina japonica*[10].

To date, primary international mechanisms for controlling exotic diseases associated with trade in aquaculture organisms and products (e.g., the Aquatic Code of the World Organisation for Animal Health (WOAH)) do not include those that impact seaweeds and aquatic plants, in that there are no international standards for the notification, diagnosis and control of diseases and pests significant to the seaweed industry. Without a clear mechanism for reporting these outbreaks from the local to the international level, they continue to occur largely under-reported in many countries. With no reporting mechanisms and evidence-based biosecurity measures in place[11], producers typically either discard diseased and pest-infested crops into the surrounding water body or attempt to treat them using 'unsanctioned' methods, such as the use of inorganic fertilizers or biological growth stimulants, attempting to increase crop resistance to disease and epiphytes[5].

In aquaculture, the lack of effective implementation and enforcement of guidelines on how to deal with infectious diseases and pests, in many cases, has led to the collapse of an industry at local and regional levels[12]. The international translocation of stock has also led to wider environmental concerns, particularly when invasive seaweeds and their associated diseases and pests have escaped and become established in the wild[6]. It is, therefore, important that the concept of biosecurity and the greater control of diseases, pests and wider environmental hazards, which can limit supply[9], are incorporated into